Supporting Information

Characterizing Aggregated Exposure to Primary Particulate Matter: Recommended Intake Fractions for Indoor and Outdoor Sources

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S-1. Input parameters for emission-to-exposure archetypes

As emission-to-exposure $PM_{2.5}$ model input, Table S1 provides numerical values for scenario-independent parameters, i.e. same values across implemented archetypes. Table S2 provides numerical values for default (global average) outdoor and indoor archetypes at *level 1*. For medium level of detail at *level 2*, Table S3 provides values for urban outdoor archetypes, Table S4 for rural outdoor archetypes, and Table S5 for residential and occupational indoor archetypes. Values for specific cities at high level of detail at *level 3* are provided in the separate Supporting Information Excel workbook.

Table S1: Numerical values for scenario-independent, constant model parameters.

Parameter	Value
Individual breathing rate	16 m^3/d [a]
Fraction of daily time spent in indoor environments	0.9 [b]
Material surface area to indoor air volume ratio	3 m^2/m^3 [c]
Average (room) height of indoor environments	3 m [a]

[a] Average across studies included in Hodas et al.,[1] not distinguishing between indoor and outdoor at global average for individual breathing rate

[b] Nazaroff and Goldstein,[2] and average across studies included in Hodas et al.[1]

[c] Lower bound of range of values reported in Singer et al.[3]

Table S2: Numerical values for *level 1* default (global average) outdoor & indoor archetypes.

Environment	Parameter	Value
Outdoor urban environment	Population count	2 million capita [a]
	Linear population density	141.4 capita/m [b]
	Urbanized air cross section area	200 km^2 [c]
	Atmospheric dilution rate	420 m^2/s [d]
	Atmospheric mixing height	119.5 m [e]
	Atmospheric particle deposition velocity	86.4 m/d [f]
Outdoor rural environment	Population count	998 million capita [g]
	Rural air cross section area	9.01×10^6 km^2 [c]
	Wind velocity	6.65 m/s [h]
	Atmospheric mixing height	1000 m [e]
	Atmospheric particle deposition velocity	418.2 m/d [i]
	Precipitation rate	700 mm/yr [j]
Indoor environment	Air exchange rate between indoor and outdoor air	0.62 hr^{-1} [k]
	Occupancy (air volume per person)	67 m^3/person [l]
	Particle deposition velocity	1 m/d [m]
	Air recirculation rate	0 d^{-1} [n]
	Efficiency of air filters	0 % [n]

$^{(a)}$ Population for representative city yielding an intake fraction close to a population-weighted average intake fraction of 39 ppm across 3646 cities from Apte et al.[4] and corresponding to the weighted average city population in year 2015[5]

$^{(b)}$ Global population-weighted average linear population density LPD [capita/m] based on fitting city-specific LPD on city-specific population POP [capita] across 3646 cities[4] as $\log(LPD) = -1.494 + 0.578 \times \log(POP)$ with $\mathrm{R}^2 = 0.62$

$^{(c)}$ City area calculated from population for representative city POP [capita] and global population-weighted average linear population density LPD [capita/m] across 3646 cities[4] as $A = (POP/LPD)^2$; global rural air cross section area including urbanized areas based on parameterized continental box[6]

$^{(d)}$ Global population-weighted normalized average atmospheric dilution rate DR [capita/m] calculated from population-weighted harmonic mean across 3646 cities from Apte et al.[4] as $\overline{DR} = \sum_l POP_l / \sum_l (POP_l / DR_l)$, where city-specific dilution rates DR_l are derived from the long-term harmonic mean of product of linearly interpolated city-specific wind speed u_l [m/s] and mixing height h_l [m] as $DR_l = 1/\left(\overline{1/u_l \times h_l}\right)$

$^{(e)}$ Global average urbanized atmospheric mixing height h [m] calculated from population-weighted harmonic mean across 3646 cities from Apte et al.[4] as $\bar{h} = \sum_l POP_l / \sum_l (POP_l / h_l)$, where city-specific mixing heights h_l are derived from the long-term harmonic mean of time-resolved mixing heights for the years 2007-2009 from NASA's Modern-Era Retrospective Analysis for Research and Applications;[7] global average atmospheric mixing height in rural areas based on parameterized continental box[6] as reported in Humbert et al.[5]

$^{(f)}$ Global average atmospheric particle deposition velocity in urban areas assuming no difference in surface roughness between different cities[8]

$^{(g)}$ Population in rural area based on parameterized continental box representing total population in a region minus the population of a single urban area[6]

$^{(h)}$ Global average wind velocity over the entire atmospheric mixing height[9]

$^{(i)}$ Global average atmospheric particle deposition velocity in rural areas[6] as function of intermittent precipitation patterns as described in Jolliet and Hauschild[10]

$^{(j)}$ Global average precipitation rate parameterized across continental regions[9]

$^{(k)}$ Average air exchange rate between indoor and outdoor air calculated from the average of air exchange rates reported for Finland, The Netherlands, Norway, Sweden, and the United States[11]

$^{(l)}$ Average air volume of indoor environments per person (occupancy) calculated from the average across studies included in Hodas et al.,[1] not distinguishing between indoor environments in urban and rural areas

$^{(m)}$ Average particle deposition velocity in indoor environments based on values reported by Nazaroff et al.,[12] and Riley et al.[13]

$^{(n)}$ Average indoor air recirculation rate and filter efficiency are assumed to be zero as baseline scenario[14]

Table S3: Model intercepts α, R^2, and standard error SE of the log for urban outdoor archetypes linear population density LPD fitted as $\log(LPD) = \alpha + 0.578 \times \log(POP)$ for global average *level 1*, and for average cities in continental and subcontinental regions at medium level of detail at *level 2*, and resulting numerical values for the fitted LPD [capita/m], and for other characteristics of average urban areas per region at *level 2*, namely city population POP [million capita], city area A [km^2], average urbanized atmospheric mixing height h [m], and average air exchange rate between indoor and outdoor air k_{ACH} [hr^{-1}]. Atmospheric dilution rates and atmospheric particle deposition velocities in urban areas at *level 2* are set equal to the global default values (see Table S2).

Geographical region		*LPD* fitting model				Other city characteristics			
		α	R^2	SE	$\boldsymbol{LPD}$	$\boldsymbol{POP}$	$\boldsymbol{A}$	$\boldsymbol{h}^{(b)}$	$\boldsymbol{k_{ACH}}^{(c)}$
Global average		−1.494	0.62	0.15	141.4	2.00	200.1	119.5	0.62
Continental regions	North America	−1.76	0.86	0.10	84.6	2.36	778.6	118.3	0.62
	Latin America	−1.57	0.76	0.12	159.9	3.34	436.3	124.9	0.62
	Europe	−1.60	0.79	0.10	94.9	1.52	256.5	109.6	0.62
	Africa & Middle East	−1.44	0.76	0.12	132.7	1.44	117.8	115.1	14
	Central Asia	−1.55	0.56	0.13	91.2	1.18	167.6	106.1	0.62
	Southeast Asia	−1.39	0.69	0.13	181.6	2.04	126.2	109.1	14
	Northern regions	−1.54	0.79	0.06	53.0	0.44	69.0	113.3	0.21
	Oceania	−1.74	0.82	0.13	47.0	0.78	275.6	183.5	0.62
Subcontinental regions$^{(a)}$	W1	−1.54	0.56	0.13	90.9	1.13	154.6	106.1	0.62
	W2	−1.42	0.74	0.12	170.2	2.02	140.8	123.6	14
	W3	−1.87	1.00	0.00	19.5	0.29	222.2	133.7	0.21
	W4	−1.71	0.83	0.12	49.5	0.77	242.0	184.8	0.62
	W5	−1.45	0.79	0.11	127.5	1.41	122.3	120.4	0.62
	W6	−1.42	0.75	0.12	133.4	1.36	104.0	113.4	14
	W7	−1.67	0.80	0.11	107.2	2.47	531.4	115.6	0.62
	W8	−1.64	0.83	0.11	127.6	2.94	530.5	125.8	0.62
	W9	−1.47	0.82	0.10	203.4	3.37	274.5	127.0	0.62
	W10	−1.75	0.86	0.10	84.1	2.25	715.0	118.3	0.62
	W12	−1.53	0.79	0.16	52.7	0.42	63.5	113.3	0.21
	W13	−1.59	0.79	0.10	94.4	1.45	235.9	109.6	0.62
	W14	−1.49	0.69	0.14	194.2	3.44	313.7	123.7	14
	IND	−1.40	0.82	0.10	223.7	3.01	181.1	108.3	14
	CHI	−1.33	0.69	0.13	157.6	1.26	63.9	106.4	0.62
	JAP	−1.52	0.72	0.13	184.4	3.44	347.8	134.0	0.62

$^{(a)}$ W1: Central Asia, W2: Indochina, W3: Northern Australia, W4: Southern Australia & New Zealand, W5: Southern Africa, W6: North, West, East & Central Africa, W7: Argentina+, W8: Brazil+, W9: Central America+ & Caribbean, W10: USA & Southern Canada, W12: Northern Europe & Northern Canada, W13: Europe, W14: East Indies & Pacific, IND: India+, CHI: Eastern China, JAP: Japan & Korean peninsula

$^{(b)}$ Median across city-specific urbanized atmospheric mixing heights per region from Apte et al.[4]

$^{(c)}$ Data based on ASHRAE 62.2,[15] Hodas et al.,[1] and Rosenbaum et al.[11]

Table S4: Numerical values for rural outdoor archetypes at medium level of detail at *level 2*, namely population POP [million capita] calculated as total rural and urban population per region minus population of average urban area per region, area A [km^2] calculated as sum of land surface and sea surface area per region, average wind velocity over the entire atmospheric mixing height u [m/s], average precipitation rate p [mm/yr], average atmospheric particle deposition velocity v_{dep} [m/d], and average air exchange rate between indoor and outdoor air k_{ACH} [hr^{-1}]. Average atmospheric mixing heights in rural areas at *level 2* are set equal to the global default value (see Table S2).

Geographical region		Rural area characteristics					
		$\boldsymbol{POP}^{(b)}$	$\boldsymbol{A}^{(b)}$	$\boldsymbol{u}^{(b)}$	$\boldsymbol{p}^{(b)}$	$\boldsymbol{v}_{\textbf{dep}}{}^{(c)}$	$\boldsymbol{k}_{\textbf{ACH}}{}^{(d)}$
Continental regions	North America	334.81	1.52×10^7	6.95	707.3	421.0	0.62
	Latin America	578.98	2.31×10^7	6.51	1612.1	666.4	14
	Europe	751.22	1.02×10^7	6.77	552.6	359.1	0.62
	Africa & Middle East	1127.13	3.49×10^7	4.26	658.2	402.1	14
	Central Asia	231.78	1.75×10^7	7.33	217.7	201.6	14
	Southeast Asia	3666.16	1.78×10^7	6.45	1516.1	647.0	14
	Northern regions	16.41	1.94×10^7	8.76	489.7	331.9	0.21
	Oceania	25.17	8.70×10^6	7.43	1295.7	598.0	0.62
Sub-continental regions$^{(a)}$	W1	231.78	1.76×10^7	7.33	217.7	201.6	14
	W2	360.29	5.46×10^6	4.86	2365.2	798.9	14
	W3	3.06	8.18×10^6	4.41	1480.8	639.5	0.62
	W4	22.11	2.19×10^6	10.45	506.7	339.4	0.62
	W5	301.45	1.08×10^7	3.45	1015.5	523.9	14
	W6	825.68	2.51×10^7	5.07	508.0	339.9	14
	W7	65.65	5.25×10^6	7.36	702.1	419.0	0.62
	W8	236.69	1.13×10^7	4.87	1765.3	695.6	14
	W9	276.64	7.27×10^6	7.32	1976.8	733.4	14
	W10	334.81	1.63×10^7	6.95	707.3	421.0	0.62
	W12	16.41	2.39×10^7	8.76	489.7	331.9	0.21
	W13	751.22	1.03×10^7	6.77	552.6	359.1	0.62
	W14	237.44	3.36×10^6	7.99	1480.8	639.5	14
	IND	1553.18	5.09×10^6	4.98	1226.4	581.1	14
	CHI	1326.73	7.27×10^6	6.11	1226.4	581.1	14
	JAP	188.51	1.02×10^6	8.33	2365.2	798.9	0.62

$^{(a)}$ W1: Central Asia, W2: Indochina, W3: Northern Australia, W4: Southern Australia & New Zealand, W5: Southern Africa, W6: North, West, East & Central Africa, W7: Argentina+, W8: Brazil+, W9: Central America+ & Caribbean, W10: USA & Southern Canada, W12: Northern Europe & Northern Canada, W13: Europe, W14: East Indies & Pacific, IND: India+, CHI: Eastern China, JAP: Japan & Korean peninsula

$^{(b)}$ Continent and subcontinent specific data based on Kounina et al.[9]

$^{(c)}$ Data as implemented in Rosenbaum et al.[6] based on intermittent rain model from Jolliet and Hauschild[10]

$^{(d)}$ Data based on ASHRAE 62.2,[15] Hodas et al.,[1] and Rosenbaum et al.[11]

Table S5: Numerical values for residential and occupational indoor archetypes at medium level of detail at *level 2*, namely average air exchange rate between indoor and outdoor air k_{ACH} [residential settings: hr^{-1}; occupational settings: m^3/hr/capita], room air volume per person (occupancy) V_{pers} [m^3/capita], air recirculation rate k_{circ} [hr^{-1}], and efficiency of air filters ε [%]. Average particle deposition velocities in residential and occupational indoor environments at *level 2* are set equal to the global default value (see Table S2).

Indoor settings		Indoor area characteristics			
		k_{ACH} [(a)]	V_{pers} [(b)]	k_{circ} [(c)]	ε [(d)]
Residential	low air exchange | no filtration/recirculation | low occupancy	0.21	100	0	0
	low air exchange | no filtration/recirculation | medium occupancy	0.21	67	0	0
	low air exchange | no filtration/recirculation | high occupancy	0.21	30	0	0
	medium air exchange | no filtration/recirculation | low occupancy	0.62	100	0	0
	medium air exchange | no filtration/recirculation | medium occupancy	0.62	67	0	0
	medium air exchange | no filtration/recirculation | high occupancy	0.62	30	0	0
	high air exchange | no filtration/recirculation | low occupancy	14	100	0	0
	high air exchange | no filtration/recirculation | medium occupancy	14	67	0	0
	high air exchange | no filtration/recirculation | high occupancy	14	30	0	0
	low air exchange | including filtration/recirculation | low occupancy	0.21	100	1	62.5
	low air exchange | including filtration/recirculation | medium occupancy	0.21	67	1	62.5
	low air exchange | including filtration/recirculation | high occupancy	0.21	30	1	62.5
	medium air exchange | including filtration/recirculation | low occupancy	0.62	100	1	62.5
	medium air exchange | including filtration/recirculation | medium occupancy	0.62	67	1	62.5
	medium air exchange | including filtration/recirculation | high occupancy	0.62	30	1	62.5
Occupational	low air exchange | low occupancy | no filtration/recirculation	9.72	5	0	0
	medium air exchange | medium occupancy | no filtration/recirculation	30.6	5	0	0
	high air exchange | high occupancy | no filtration/recirculation	46.8	10	0	0
	low air exchange | low occupancy | including filtration/recirculation	9.72	5	5	62.5
	medium air exchange | medium occupancy | including filtration/recirculation	30.6	5	5	62.5

[(a)] Residential: low air exchange rate calculated from 35 L/s reported in ASHRAE 62.2 (bedrooms with 4 to 5 persons and a floor area of 139.1 to 279 m^2)[15] and a standard room area of 200 m^2, medium air exchange rate calculated from average values reported for Finland, The Netherlands, Norway, Sweden, and the United States,[11] and high air exchange rate based on average across values reported in Hodas et al.[1]; occupational (m^3/hr/capita): low equivalent air exchange rate calculated from 2.7 L/s/capita reported in ASHRAE 62.1 (auditorium seating area + lobbies),[16] medium equivalent air exchange rate calculated from 8.5 L/s/capita reported in ASHRAE 62.1 (office space),[16] and high equivalent air exchange rate calculated from 13 L/s/capita reported in ASHRAE 62.1 (health club/weight rooms)[16]

[(b)] Average low, medium and high occupancies calculated from upper range, average and lower range of values across studies included in Hodas et al.[1]

[(c)] High recirculation removal rates based on values reported in Chen et al.[17] assuming 20% daily runtime reported for air conditioning systems in residential buildings[18], while assuming 100% daily runtime in occupational buildings, i.e. systems always run during working hours

[(d)] High filter efficiencies based on an average over the range between 40 and 85% of ASHRAE 52.2 MERV classes 9-12 for Intended Dust Spot Efficiency for superior residential buildings[19]

S-2. Correction of outdoor urban to rural air transfer

The transfer from outdoor urban air to outdoor rural air was adjusted by considering city-specific dynamics as a function of fitting area and dilution rate across cities in a correction factor. This correction factor improves the correlation between intake fraction and the rate coefficient linking the urban area to its background rural environment compared to a direct transfer only based on dilution rate and size of the urban area, i.e. without involving the linear population density. The correction factor $f_{\mathrm{u,corr}}$ was derived as follows:

We start from the intake fraction $iF_{\mathrm{o,u}}$ related to the transfer from outdoor urban to rural air $k_{\mathrm{o,r\leftarrow o,u}}$ and the exposure factor from outdoor urban air via inhalation $XF_{\mathrm{o,u}}$:

$$iF_{\mathrm{o,u}} = \frac{XF_{\mathrm{o,u}}}{k_{\mathrm{o,r\leftarrow o,u}}} \tag{S1}$$

where

$$XF_{\mathrm{o,u}} = \frac{BR_{\mathrm{o}} \times POP_{\mathrm{u}}}{V_{\mathrm{o,u}}} = \frac{BR_{\mathrm{o}} \times POP_{\mathrm{u}}}{h_{\mathrm{o,u}} \times A_{\mathrm{o,u}}} \tag{S2}$$

and

$$k_{\mathrm{o,r\leftarrow o,u}} = \frac{DR_{\mathrm{o,u}}}{h_{\mathrm{o,u}} \times \sqrt{A_{\mathrm{o,u}}}} \times f_{\mathrm{u,corr}} \tag{S3}$$

with breathing rate BR, human population count POP, air volume V, atmospheric mixing height h, and air cross section area A, normalized atmospheric dilution rate DR, and correction factor accounting for city-specific dynamics in area and dilution rate $f_{\mathrm{u,corr}}$. Integrating eqs. S2 and S3 into eq. S1 yields

$$iF_{\mathrm{o,u}} = \frac{BR_{\mathrm{o}}}{DR_{\mathrm{o,u}} \times f_{\mathrm{u,corr}}} \times \frac{POP_{\mathrm{u}}}{\sqrt{A_{\mathrm{o,u}}}} \tag{S4}$$

When defining the linear population density LPD as[4]

$$LPD = \frac{POP_{\mathrm{u}}}{\sqrt{A_{\mathrm{o,u}}}} \tag{S5}$$

and correcting units for $A_{\mathrm{o,u}}$ from km^2 to m^2 and for $DR_{\mathrm{o,u}}$ from seconds to days allows to fit the ratio of $iF_{\mathrm{o,u}}$ and LPD as function of $A_{\mathrm{o,u}}$ and $DR_{\mathrm{o,u}}$ across all 3646 cities reported in Apte et al.,[4] yielding an intercept $\alpha = 1.84$, and regression coefficients for area, $\beta_A = -0.0508$, and for dilution rate, $\beta_{DR} = -0.0508$, with $R^2 = 0.96$ and standard error on the log, $SE = 0.037$:

$$\frac{iF_{\mathrm{o,u}}}{LPD} = \frac{BR_{\mathrm{o}}}{DR_{\mathrm{o,u}} \times f_{\mathrm{u,corr}}} = 10^{1.84} \times A^{-0.0508} \times DR^{-0.876} \tag{S6}$$

Eq. S6 can be solved for $f_{\mathrm{u,corr}}$ as

$$f_{\mathrm{u,corr}} = \frac{BR_{\mathrm{o}}}{10^{1.84}} \times A^{0.0508} \times DR^{-0.124} \tag{S7}$$

Using our default breathing rate of $BR = 14.5$ m^3/d then yields our final correction factor:

$$f_{\mathrm{u,corr}} = 4.95 \times A^{0.0508} \times DR^{-0.124} \tag{S8}$$

S-3. Estimating urban population and city area for given regions

Urban area and population for a given city must be consistently derived for any average city at any spatial level (e.g. subcontinental, continental, or global). Consistency between these parameters is ensured by using the linear population density (see eq. S5). We start from eq. S6 and solve it for intake fraction $iF_{\mathrm{o,u}}$:

$$iF_{\mathrm{o,u}} = 10^{1.84} \times A^{-0.0508} \times DR^{-0.876} \times LPD \qquad \text{(S9)}$$

Using the relation $A = (POP/LPD)^2$ derived from eq. S5 and the general model to fit LPD for any city in a given region x as $\log(LPD) = \alpha_x + \beta \times \log(POP)$ (see main text and Table S3), we can substitute LPD in eq. S9 as

$$iF_{\mathrm{o,u}} = 10^{1.84} \times DR^{-0.876} \times (\overbrace{(POP/10^{\alpha_x+\beta\times\log(POP)})^2}^{A})^{-0.0508} \times \overbrace{10^{\alpha_x+\beta\times\log(POP)}}^{LPD} \qquad \text{(S10)}$$

which we can simplify to

$$iF_{\mathrm{o,u}} = 10^{1.84} \times DR^{-0.876} \times 10^{1.1016\times\alpha_x} \times POP^{1.1016\times\beta-0.1016} \qquad \text{(S11)}$$

To finally back-calculate the population for an average city for a given region that yields an exposure close to the population-weighted average urban intake fraction of this region, we can solve eq. S11 for POP as

$$POP = \left(\frac{iF_{\mathrm{o,u}}}{10^{1.84}\times DR^{-0.876}\times 10^{1.1016\times\alpha_x}}\right)^{(1.1016\times\beta-0.1016)^{-1}} \qquad \text{(S12)}$$

and additionally yield a corresponding urban area (see main text, Table 1) of

$$A = \left(POP/10^{\alpha_x+\beta\times\log(POP)}\right)^2 = \left(10^{-\alpha_x} \times POP^{1-\beta}\right)^2 \qquad \text{(S13)}$$

S-4. $PM_{2.4}$ indoor-outdoor emission-to-exposure model

The complete $PM_{2.5}$ indoor-outdoor emission-to-exposure modeling framework is implemented as a Microsoft Excel spreadsheet and is provided free-of-charge in a separate Supporting Information file to this publication.

References

(1) Hodas, N.; Loh, M.; Shin, H.-M.; Li, D.; Bennett, D.; McKone, T. E.; Jolliet, O.; Weschler, C. J.; Jantunen, M.; Lioy, P.; Fantke, P., Indoor inhalation intake fractions of fine particulate matter: Review of influencing factors. *Indoor Air* **2016,** *26*, 836-856, doi:10.1111/ina.12268.

(2) Nazaroff, W. W.; Goldstein, A. H., Indoor chemistry: Research opportunities and challenges. *Indoor Air* **2015,** *25*, 357-361, doi:10.1111/ina.12219.

(3) Singer, B. C.; Hodgson, A. T.; Hotchi, T.; Ming, K. Y.; Sextro, R. G.; Wood, E. E.; Brown, N. J., Sorption of organic gases in residential rooms. *Atmos. Environ.* **2007,** *41*, 3251-3265, doi:10.1016/j.atmosenv.2006.07.056.

(4) Apte, J. S.; Bombrun, E.; Marshall, J. D.; Nazaroff, W. W., Global intraurban intake fractions for primary air pollutants from vehicles and other distributed sources. *Environ. Sci. Technol.* **2012,** *46*, 3415-3423, doi:10.1021/es204021h.

(5) Humbert, S.; Marshall, J. D.; Shaked, S.; Spadaro, J. V.; Nishioka, Y.; Preiss, P.; McKone, T. E.; Horvath, A.; Jolliet, O., Intake fraction for particulate matter: Recommendations for life cycle impact assessment. *Environ. Sci. Technol.* **2011,** *45*, 4808-4816, doi:10.1021/es103563z.

(6) Rosenbaum, R. K.; Bachmann, T. M.; Gold, L. S.; Huijbregts, M. A. J.; Jolliet, O.; Juraske, R.; Koehler, A.; Larsen, H. F.; MacLeod, M.; Margni, M. D.; McKone, T. E.; Payet, J.; Schuhmacher, M.; van de Meent, D.; Hauschild, M. Z., USEtox - The UNEP-SETAC toxicity model: Recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *Int. J. Life Cycle Assess.* **2008,** *13*, 532-546, doi:10.1007/s11367-008-0038-4.

(7) Rienecker, M. M.; Suarez, M. J.; Gelaro, R.; Todling, R.; Bacmeister, J.; Liu, E., et al., MERRA: NASA's modern-era retrospective analysis for research and applications. *J. Clim.* **2011,** *24*, 3624-3648, doi:10.1175/JCLI-D-11-00015.1.

(8) Seinfeld, J. H.; Pandis, S. N., *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change, Second Edition*. John Wiley and Sons: New York, 2006.

(9) Kounina, A.; Margni, M.; Shaked, S.; Bulle, C.; Jolliet, O., Spatial analysis of toxic emissions in LCA: A sub-continental nested USEtox model with freshwater archetypes. *Environ. Int.* **2014,** *69*, 67-89, doi:10.1016/j.envint.2014.04.004.

(10) Jolliet, O.; Hauschild, M. Z., Modeling the influence of intermittent rain events on long-term fate and transport of organic air pollutants. *Environ. Sci. Technol.* **2005,** *39*, 4513-4522.

(11) Rosenbaum, R. K.; Meijer, A.; Demou, E.; Hellweg, S.; Jolliet, O.; Lam, N. L.; Margni, M.; McKone, T. E., Indoor air pollutant exposure for life cycle assessment: Regional health impact factors for households. *Environ. Sci. Technol.* **2015,** *49*, 12823-12831, doi:10.1021/acs.est.5b00890.

(12) Nazaroff, W. W.; Gadgil, A. J.; Weschler, C. J., Critique of the use of deposition velocity in modeling indoor air quality. *ASTM Spec. Tech. Publ.* **1993,** *1205*, 81-104, doi:10.1520/10.1520/STP13101S.

(13) Riley, W. J.; McKone, T. E.; Lai, A. C. K.; Nazaroff, W. W., Indoor particulate matter of outdoor origin: Importance of size-dependent removal mechanisms. *Environ. Sci. Technol.* **2002,** *36*, 200-207, doi:10.1021/es010723y.

(14) Fisk, W. J., Health benefits of particle filtration. *Indoor Air* **2013,** *23*, 357-368, doi:10.1111/ina.12036.

(15) ASHRAE American Society of Heating, R. a. A.-C. E. *ANSI/ASHRAE Standard 62.2-2013 - Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*; Atlanta, GA, 2013.

(16) ASHRAE American Society of Heating, R. a. A.-C. E. *ANSI/ASHRAE Standard 62.1-2013 - Ventilation for Acceptable Indoor Air Quality*; Atlanta, GA, 2013.

(17) Chen, C.; Zhao, B.; Weschler, C. J., Indoor exposure to "outdoor PM_{10}": Assessing its influence on the relationship between PM_{10} and short-term mortality in U.S. cities. *Epidemiology* **2012,** *23*, 870-878, doi:10.1097/EDE.0b013e31826b800e.

(18) Cetin, K. S.; Novoselac, A., Single and multi-family residential central all-air HVAC system operational characteristics in cooling-dominated climate. *Energy Build.* **2015,** *96*, 210-220, doi:10.1016/j.enbuild.2015.03.039.

(19) ASHRAE American Society of Heating, R. a. A.-C. E. *ANSI/ASHRAE Standard 52.2-2017 - Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*; Atlanta, GA, 2017.